



# Testing Einstein's Equivalence Principle with supercluster Laniakea's gravitational field



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## ABSTRACT

Comparing the parameterized post-Newtonian parameter  $\gamma$  values for different types of particles, or the same type of particles with different energies is an important method to test the Einstein Equivalence Principle (EEP). Assuming that the observed time delays are dominated by the gravitational potential of the Laniakea supercluster of galaxies, better results of EEP constraints can be obtained. In this paper, we apply photons from three kinds of cosmic transients, including TeV blazars, gamma-ray bursts as well as fast radio bursts to constrain EEP. With a gravitational field far more stronger than a single galaxy, we obtain 4–5 orders of magnitude more stringent than the previous results.

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## 1. Introduction

The Einstein Equivalence Principle (EEP) stands as one of the most important basic assumptions as well as cornerstones of general relativity, along with many other metric theories of gravity. According to EEP, the traveling path of any uncharged test object in vacuum is independent of the object's internal structure and composition. All metric gravity theories taking EEP as assumption predict one of the parameterized post-Newtonian (PPN) parameter  $\gamma_1 = \gamma_2 \equiv \gamma$ , where the subscripts 1 and 2 denote two different test particles (such as photons or neutrinos), respectively (Will, 2006, 2014). So the accuracy of the EEP can be constrained by comparing the value of  $\gamma$  for different types of particles, or the same type of particles with different energies.

Many methods have been developed to test the EEP with high accuracy by the measurement of the value of  $\gamma$ . One of the most successful methods, which measures the gravitational deflection of light near the Sun and the round-trip travel time delay of artificial radar signal due to the solar system gravity, yields  $\gamma - 1 = (-0.8 \pm 1.2) \times 10^{-4}$  (Lambert and Le Poncin-Lafitte, 2009, 2011) and  $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$  (Bertotti et al., 2003). Recently, EEP has also been tested using the time delay of photons with different energies arising in single cosmic transient event, such as gamma-ray bursts (GRBs; Gao et al., 2015), fast radio bursts (FRBs; Wei et al., 2015; Tingay and Kaplan, 2016), and TeV blazars

(Wei et al., 2016). These results have been improved for several orders of magnitude compared with previous works, that is,  $\gamma_{\text{GeV}} - \gamma_{\text{MeV}} < 2 \times 10^{-8}$  for GRB 090510 (Gao et al., 2015), and  $\gamma_{1.23 \text{ GHz}} - \gamma_{1.45 \text{ GHz}} < 4.36 \times 10^{-9}$  for FRB 100704 (Wei et al., 2015), and  $\gamma_{(0.2 \text{ TeV}-0.8 \text{ TeV})} - \gamma_{(>0.8 \text{ TeV})} < 2.18 \times 10^{-6}$  for TeV blazar PKS 2155-304 (Wei et al., 2016). Very recently, such EEP tests have also been applied to gravitational waves (Wu et al., 2016; Kahya and Desai, 2016).

In all these works, to account for the time delay of the photons, gravitational fields taken into consideration were from Milky Way only. However as mentioned by Nusser (2016), Zhang (2016), and Wang et al. (2016), larger scale structures, such as galaxy clusters and other large scale fluctuations have stronger gravitational potentials, thus may cause larger delay between different particles. Such structures can provide even better constraints on EEP. In this work we test the EEP with photons from various astrophysical transients, adopting the Laniakea, the supercluster in which Milky Way resides as our source of gravitational field. Since Laniakea supercluster of galaxies is much more massive than a single galaxy, more stringent constraints can be obtained. In Section 2 of this paper, our basic methods are described. Our results are presented in Section 3. In Section 4, this analysis is discussed and summarized.

## 2. Constraining EEP with gravitational field of Laniakea

Superclusters are the most massive structure in cosmic scales. Although each member cluster of galaxies is not affected by mutual gravitational forces, supercluster can influence not only the motions of its member clusters, but also the expansion of the

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Universe itself. Laniakea is a newly discovered supercluster of galaxies to which the Milky Way galaxy belongs (Tully et al., 2014). This supercluster encompasses some 100,000 galaxies in 300 to 500 galaxy clusters, and stretches more than 500 million light-years. The total mass of the Laniakea is  $10^{17}$  solar masses, which is nearly a hundred thousand times that of our Milky Way galaxy.

The limits on the differences in PPN parameters for difference particles determine the accuracy of EEP. For example, it has been shown that the time interval required for photons to traverse a given distance is longer in the presence of a gravitational potential  $U(r)$  by

$$\Delta t = -\frac{1+\gamma}{c^3} \int_{r_e}^{r_o} U(r) dr, \quad (1)$$

where  $r_e$  and  $r_o$  are the locations of the emission and observation, respectively (Shapiro, 1964; Longo, 1988; Krauss and Tremaine, 1988). Here  $\gamma$  is one of the PPN parameters, representing the space curvature produced by unit rest mass.  $\gamma$  is found to be nearly unity, consistent with the prediction of  $\gamma = 1$  by general relativity (Will, 1993). However, in testing EEP, a more important question is whether different types of particles share the same value of  $\gamma$ , rather than the absolute value of  $\gamma$ .

As shown in Gao et al. (2015) and Wei et al. (2015), for a cosmic transient source, the various terms that might contribute to the observed time delay between two different energy bands may be expressed as follows:

$$\Delta t_{\text{obs}} = \Delta t_{\text{int}} + \Delta t_{\text{LIV}} + \Delta t_{\text{spe}} + \Delta t_{\text{DM}} + \Delta t_{\text{gra}}. \quad (2)$$

Here  $\Delta t_{\text{int}}$  is the intrinsic (astrophysical) time delay between two test photons. It is hard to estimate the exact value of  $\Delta t_{\text{int}}$ , since the inner workings of such events can be complicated and are model-dependent. Thus in our analysis we assume  $\Delta t_{\text{int}} = 0$  and an upper limit of time delay induced by EEP can be achieved.  $\Delta t_{\text{LIV}}$  is the time delay from the Lorentz invariance violation. It is ignored in the following analysis, since current observations have already put very stringent limits on this term (e.g., see Vasileiou et al., 2013).  $\Delta t_{\text{spe}}$  is the potential time delay due to special-relativistic effects with non-zero photon rest mass. Modern experiments have showed that  $\Delta t_{\text{spe}}$  is negligible even when the energy of test photons is lower than radio band (e.g., see Ryutov, 2007).  $\Delta t_{\text{DM}}$  represents the time delay contributed by the dispersion from the line-of-sight free electron content, which is non-negligible especially for low energy photons (e.g., radio signals).  $\Delta t_{\text{gra}}$  corresponds to the difference in arrival time of two photons of energy  $E_1$  and  $E_2$ , caused by the gravitational potential  $U(r)$  integrated from the emission source to Earth. From Equation (1) we can write

$$\Delta t_{\text{gra}} = \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U(r) dr, \quad (3)$$

where  $U(r)$  can be decomposed into three components, that is, the gravitational fields of the host galaxy of the transient, intergalactic background field, as well as Laniakea supercluster of galaxies in which the Milky Way galaxy as well as the Local Group reside. Since in the local universe the contribution from home supercluster can dominate the other two components, in this analysis we only consider the contribution from the Laniakea  $U_L(r)$ . Thus we have

$$\Delta t_{\text{gra}} = \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U_L(r) dr. \quad (4)$$

Assuming  $\Delta t_{\text{int}} > 0$  and casting off the negligible components, we have

$$\Delta t_{\text{obs}} - \Delta t_{\text{DM}} > \frac{\gamma_1 - \gamma_2}{c^3} \int_{r_o}^{r_e} U_L(r) dr. \quad (5)$$

Although the gravitational potential of the Laniakea  $U_L(r)$  at large distances is still not known, we still adopt the Keplerian potential  $U_L(r) = -GM/r$  here. Thus we have (Longo, 1988)

$$\Delta t_{\text{obs}} > (\gamma_1 - \gamma_2) \frac{GM_L}{c^3} \times \ln \left\{ \frac{\left[ d + (d^2 - b^2)^{1/2} \right] \left[ r_L + s_n (r_L^2 - b^2)^{1/2} \right]}{b^2} \right\}, \quad (6)$$

where  $G = 6.68 \times 10^{-8} \text{ erg cm g}^{-2}$  is the gravitational constant,  $M_L \simeq 1 \times 10^{17} M_\odot$  is the Laniakea mass (Tully et al., 2014),  $c = 3 \times 10^{10} \text{ cm s}^{-1}$  is the energy-independent speed for massless particles,  $d$  is the distance from the source to the Laniakea center (if the source is of cosmological origin,  $d$  is approximated as the distance from the source to the Earth),  $b$  is the impact parameter of the light rays relative to the Laniakea center, and  $s_n = \pm 1$  represents the sign of the correction of the source direction. If the source is located along the direction of Laniakea center,  $s_n = +1$ . While,  $s_n = -1$  corresponds to the source located along the direction of anti-Laniakea center. However, the center coordinates of Laniakea itself are not well estimated. Since the gravitational center of Laniakea is believed to be the so-called Great Attractor (Lynden-Bell et al., 1988), a gravity anomaly in intergalactic space within the vicinity of the Hydra-Centaurus Supercluster that reveals the existence of a localized concentration of mass tens of thousands of times more massive than the Milky Way (Tully et al., 2014), we consider the center of the Great Attractor instead (i.e., R.A. =  $10^{\text{h}}32^{\text{m}}$ , decl. =  $-46^\circ00'$ ). For a cosmic source in the direction (R.A. =  $\beta_s$ , decl. =  $\delta_s$ ), the impact parameter can be expressed as

$$b = r_L \sqrt{1 - (\sin \delta_s \sin \delta_L + \cos \delta_s \cos \delta_L \cos(\beta_s - \beta_L))^2}, \quad (7)$$

where  $r_L = 79 \text{ Mpc}$  is the distance from the Earth to the Laniakea center, and  $(\beta_L = 10^{\text{h}}32^{\text{m}}, \delta_L = -46^\circ00')$  are the coordinates of the Laniakea center in the equatorial coordinate system.

### 3. Test the EEP with cosmic transient events

It can be seen from the previous section that the larger the distance of the transient, the shorter the time delay, the better the EEP constraint. Flares of TeV blazars, GRBs as well as FRBs are among common transients in the Universe. All of these events are thought to be extragalactic origins, and have short intrinsic variation time scales, thus providing ideal testbed for obtaining EEP constraints. In our analysis, we select some examples from each of these three groups.

As a subclass of active galactic nuclei, the blazars can be divided into flat spectrum radio quasars if they have strong emission lines and BL Lacertae or not. The broadband non-thermal emission of blazars extends from radio up to high-energy and very-high-energy (Ulrich et al., 1997). Because of their cosmological distances, fast variability as well as VHE photons emitted in the TeV band, such TeV blazars can be used to constrain EEP (Wei et al., 2016). Since the TeV blazar PKS 2155-304 with a redshift of  $z = 0.117$  (Shimmings and Bolton, 1974) lies beyond the realm of Laniakea, we can constrain EEP with time delay in Laniakea's gravitational field with this source. Its coordinates (J2000)

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